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New High-Altitude GPS Navigation Results from the Magnetospheric Multiscale Spacecraft and Simulations at Lunar Distances

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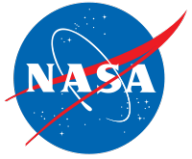
***NASA Goddard Space Flight Center**

****Emergent Space Technologies, Inc.**

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Outline

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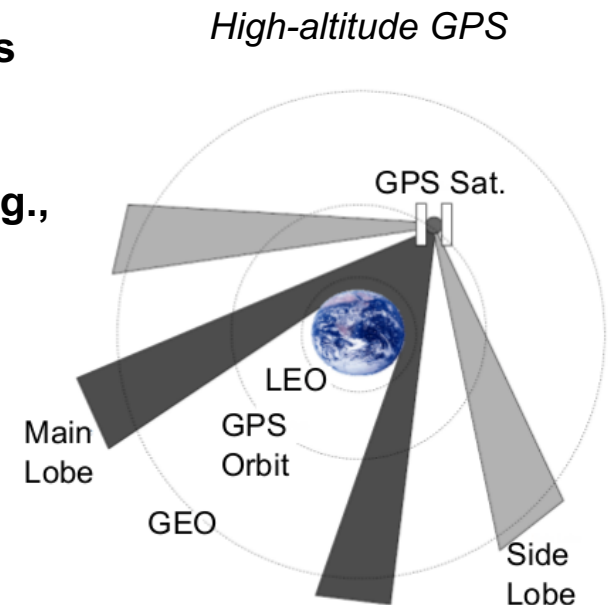
- **Background**
 - High altitude GPS
 - Magnetospheric Multiscale (MMS) Mission
 - GPS Navigation for MMS
 - MMS Mission
 - MMS Navigation system
- **New results from MMS Phase 2B**
- **Simulations at Lunar distance**
 - Calibration on MMS Phase 2B
 - MMS extended mission concept
 - Concept Lunar trajectory
- **Conclusion**

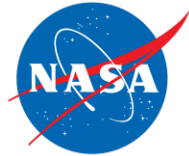


Background on high-altitude (HEO) GPS

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- **HEO GPS navigation offers performance and cost improvements, but poses challenges**
 - Sparse mainlobe availability, sidelobes weak, unspecified/uncharacterized, poor geometry, potentially harsher radiation environment.
- **Ongoing research in HEO GPS R&D since 1990's, GSFC among leaders**
 - Numerous simulations studies at GEO, HEO, even Lunar distances
 - GSFC led effort to define/expand GPS Space Service Volume definition and characterize in-situ GPS transmitter antenna patterns (GPS-ACE 2015)
 - Developed Navigator HEO GPS receiver
- **Early on-orbit experiments in late 1990's-early 2000's**
 - AFRL Falcon Gold, TEAMSAT, EQUATOR-S
 - NASA GSFC / AMSAT OSCAR-40, 2000
- **Recent growth in available receivers/applications, e.g.,**
 - GD Monarch flying on USG SBIRS (GEO) (~2011-2012)
 - Surrey Satellite SGR-GEO experiment on GIOVE-A (2013)
 - Airbus/Astrium MosaicGNSS and LION GNSS Rx for HEO
 - Moog-Broad Reach Navigator (AFRL ANGELS 2015, EAGLE 2017)
 - RUAG Podrix to fly on ESA Proba-3 (2018)
 - *General Dynamics' Viceroy-4 flying GOES-16 at GEO (2017)*
 - ***NASA GSFC Navigator GPS flying HEO MMS since 3/2015***
- **MMS set records for highest (and fastest) GPS receiver operations to date**

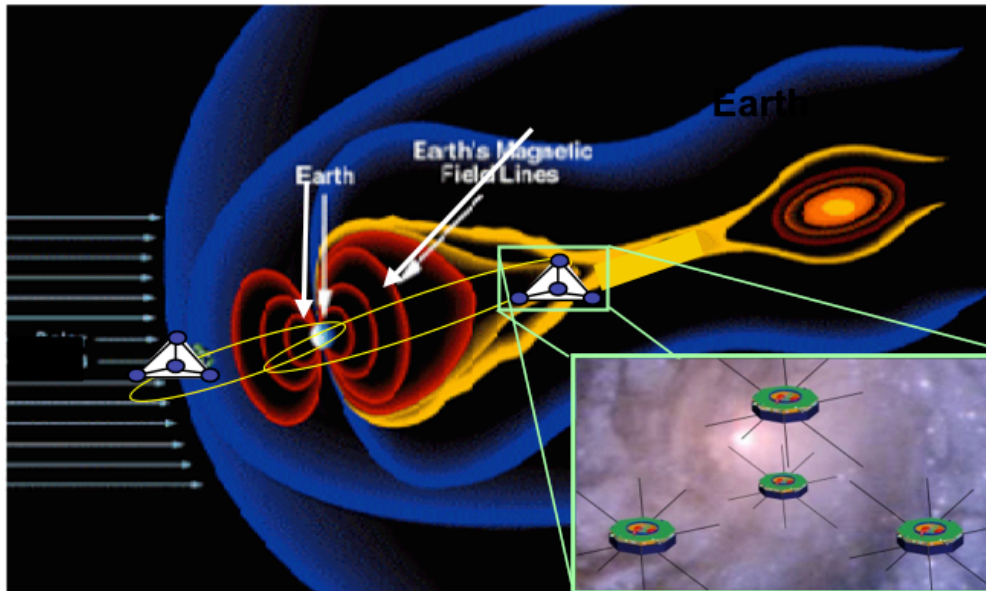




Magnetospheric Multiscale Mission (MMS)

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- Discover the fundamental plasma physics process of reconnection in the Earth's magnetosphere.
- Coordinated measurements from tetrahedral formation of four spacecraft with scale sizes from 400km to 7km
- Flying in two highly elliptic orbits in two mission phases
 - Phase 1 $1.2 \times 12 R_E$ (magnetopause)
 - Phase 2B $1.2 \times 25 R_E$ (magnetotail)
(For reference GEO $\sim 6.5 R_E$, Moon $\sim 60 R_E$)

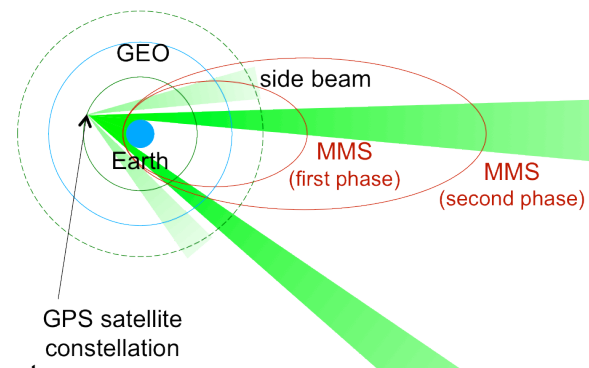




MMS Navigation System

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- **MMS Navigation system consists of Navigator GPS receiver, with Ultra-stable crystal oscillator and Goddard Enhanced Onboard Navigation Software (GEONS)**
- **Navigator-GPS**
 - Product of NASA Goddard project to build high-altitude GPS receiver (~2001)
 - Rad-hard C/A code receiver, with fast unaided weak signal acq (<25dB-Hz)
 - Heritage on STS-125 Relative Navigation Sensor Experiment (2009), Global Precipitation Measurement Mission (GPM, 2014-), Tech incorporated into Honeywell Orion GPS - demo on EFT-1 of fast-acq for rapid recovery from blackout (Dec 2014)
- **GEONS**
 - UD-factorized Extended Kalman Filter, 4th/8th order RK integrator, realistic process noise models. High-fidelity dynamics and many measurement models available.
 - Development dates back to 1980's on Cosmic Origins Background Explorer (COBE).
 - Flying on Terra, GPM, NICER, SEXTANT, MMS, planned on Restore-L, possible WFIRST.
- **MMS-GEONS**
 - Estimate absolute pos/vel, clock bias, rate & accel, integrator step 10s
 - 13x13 geopotential, sun, moon point mass, SRP, drag
 - Process L1 C/A GPS undifferenced pseudorange at 30s rate
 - Accelerometer data at 10s during maneuver
- **MMS Navigation main challenges**
 - Sparse, weak, poorly characterized signal signal environment, poor geometry
 - Spacecraft spin stabilized at 3RPM; obstructions on top and bottom of spacecraft drove to four antennas around perimeter, receiver implements handoff tracking technique antenna-to-antenna every 5s



MMS Navigator GPS hardware

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- GPS hardware all developed and tested at GSFC. Altogether, 8 electronics boxes, 8 USOs, 32 antennas and front ends

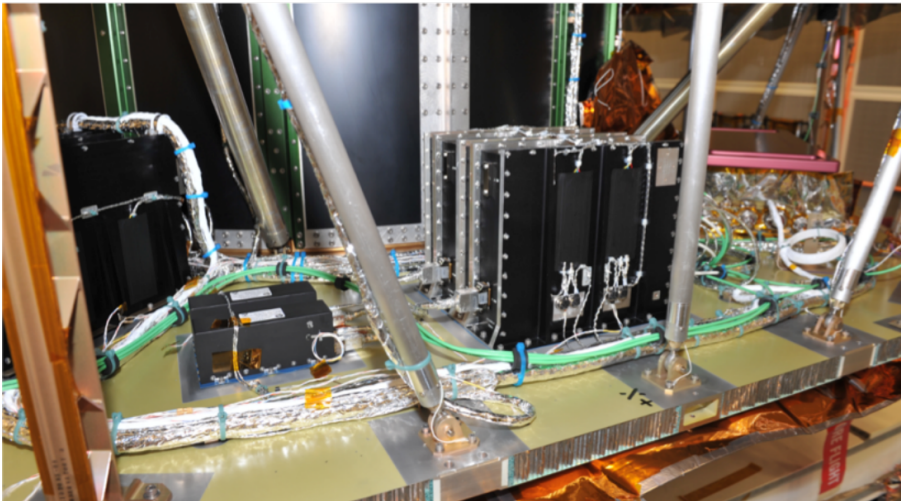
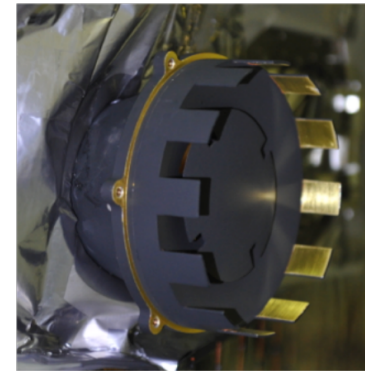
Ultra Stable Osc.



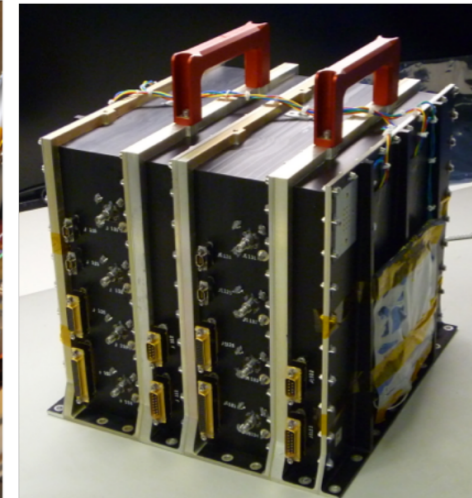
Front end electronics assembly



GPS antenna



Receiver and USO on spacecraft deck



Redundant receiver electronics



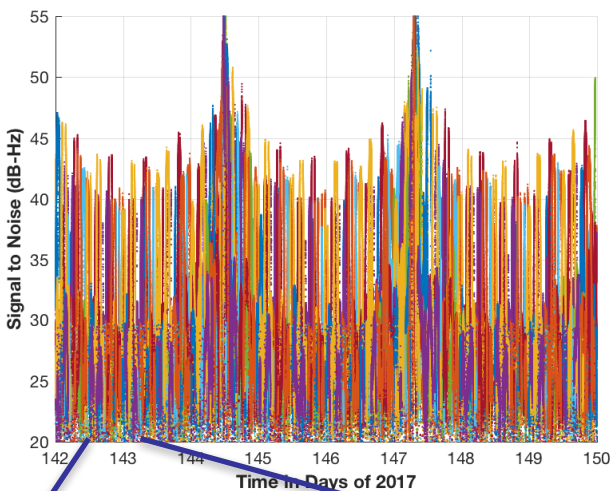
On-orbit Phase 2B results: signal tracking



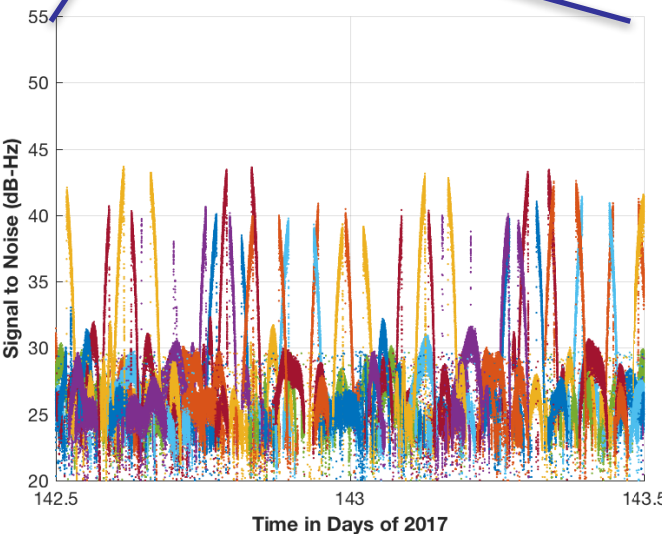
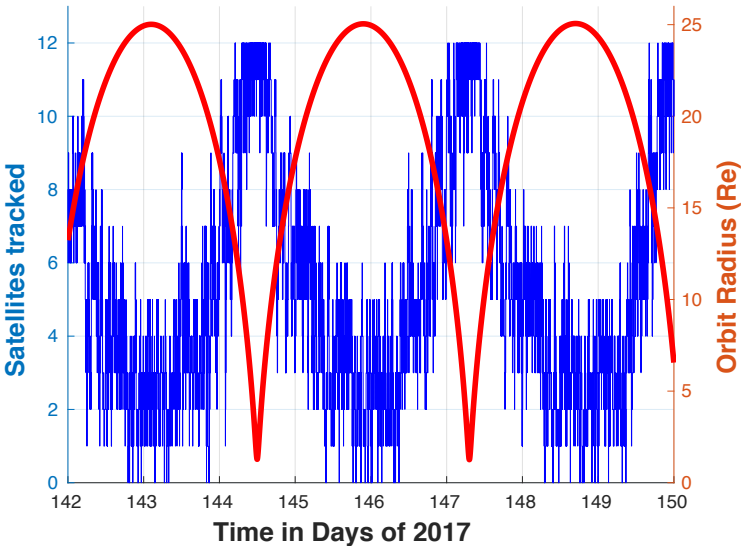
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- Consider 8-day period early in Phase 2B
- Above GPS constellation, majority of signals are still sidelobes
- Long term trend shows average of ~3 signals tracked near apogee, with up to 8 observed.
- Visibility exceeds preflight expectations significantly

C/N₀ vs. time, near apogee



Signals tracked

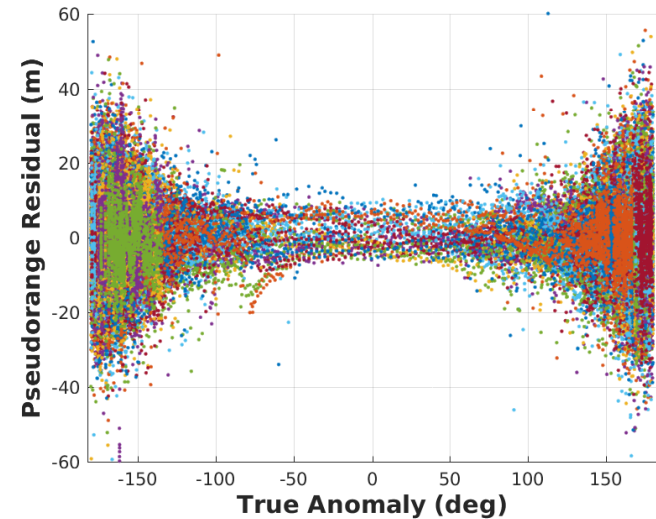




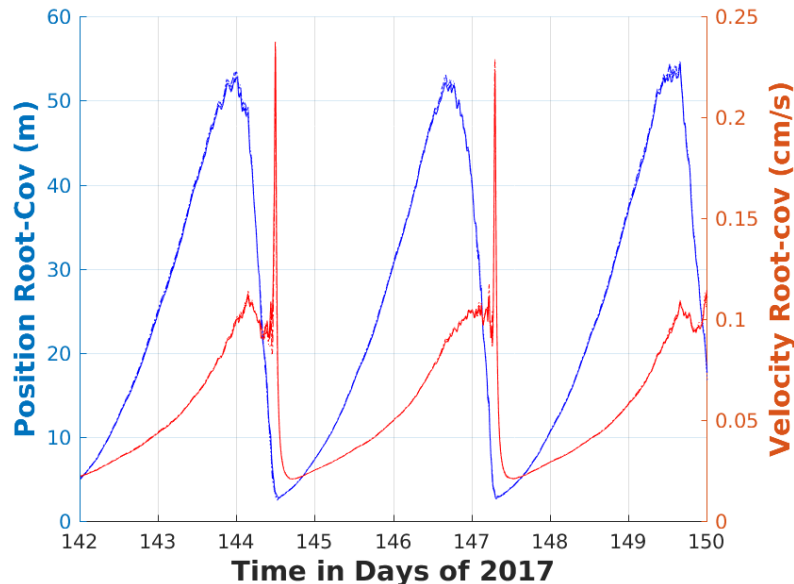
On-orbit Phase 2B results: measurement and navigation performance

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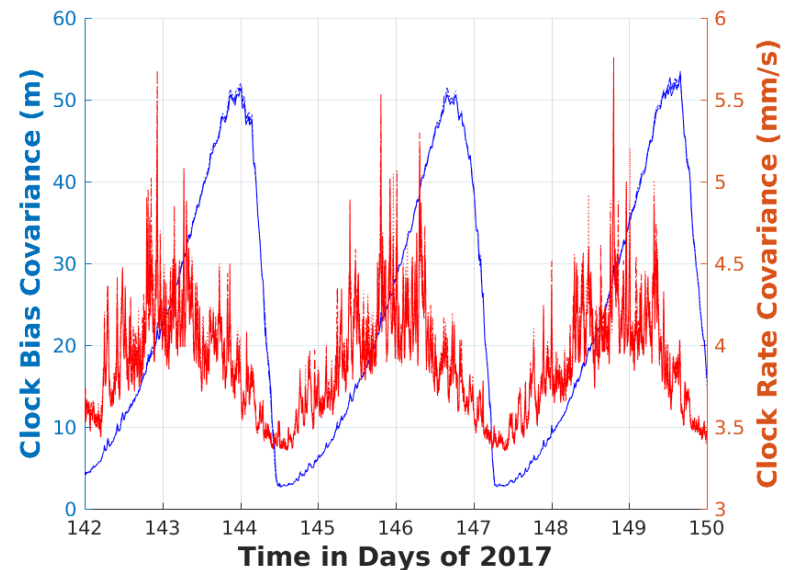
- GEONS filter RSS 1-sigma formal errors reach maximum of ~50m and briefly 5mm/s (typically <1mm/s)
- Measurement residuals are zero mean, of expected variation <10m 1-sigma.
 - Suggests sidelobe measurements are of high quality.

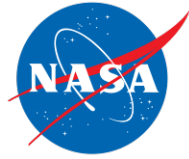


Filter formal pos/vel errors (1σ root cov)



Filter formal clock errors (1σ root cov)

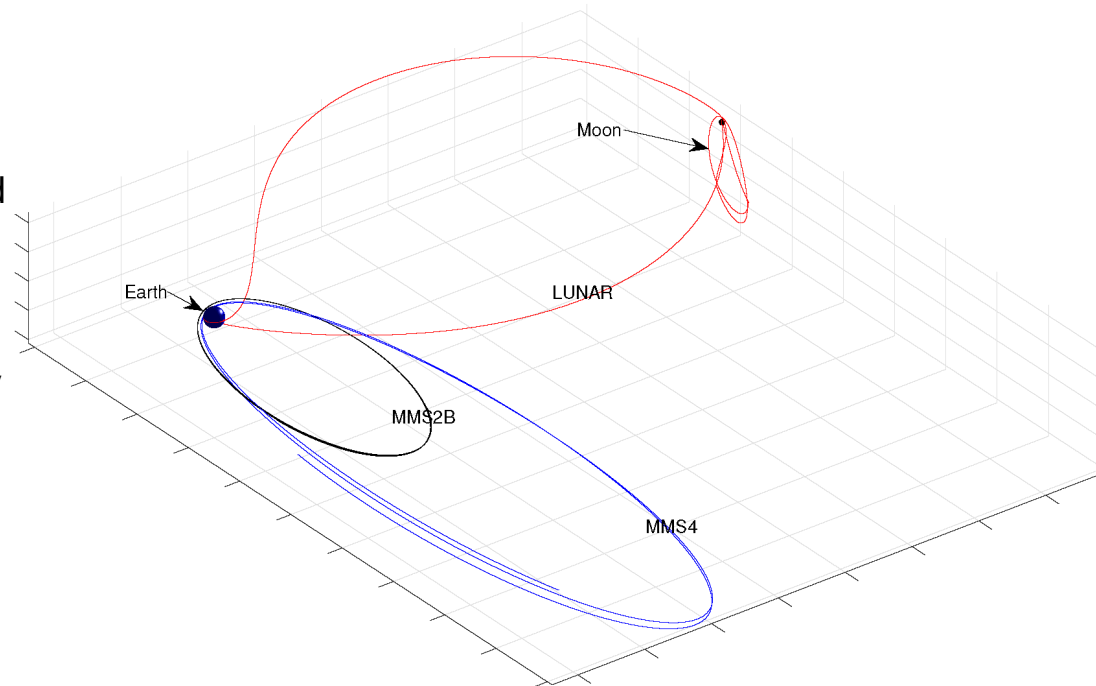


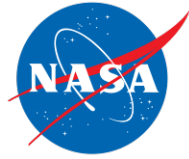


Simulations

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- **Wanted to “get a feel for” performance of MMS Navigation system in:**
 1. A concept MMS extended mission orbit with apogee raised to 60 RE
 2. A concept Lunar trajectory
- **Ran “quick” GEONS ground simulations using new flexible MATLAB based GEONS simulation architecture using GEONS-*Datagen* GPS data simulation**
 - Very similar approach to MMS preflight analysis, but with link models recalibrated based on on-orbit observations in Phase 2B
 - Model MMS GPS receiver performance
 - Run GEONS FSW as configured for MMS
 - Simulation used higher order dynamics than filter, but included some simplifications
 - None or impulsive burns
 - No SRP or drag
 - Ran one case for each trajectory considered
 - Examined visibility, tracking performance, filter formal and actual errors

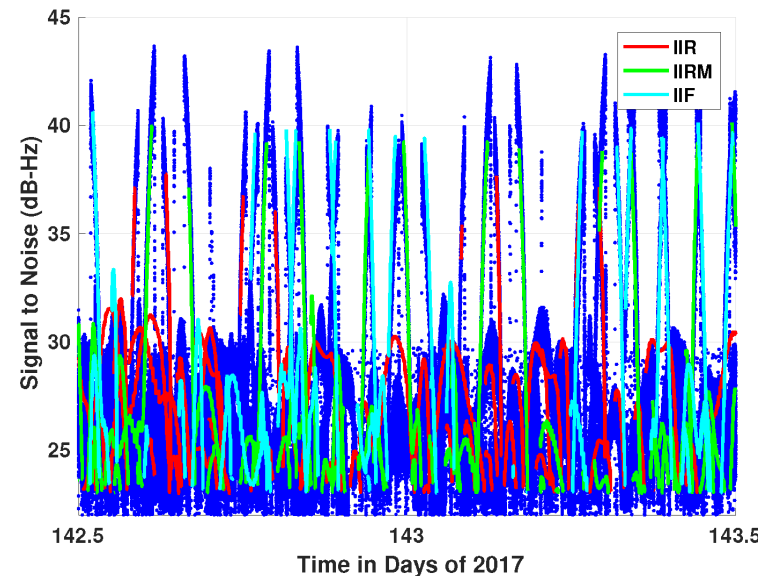
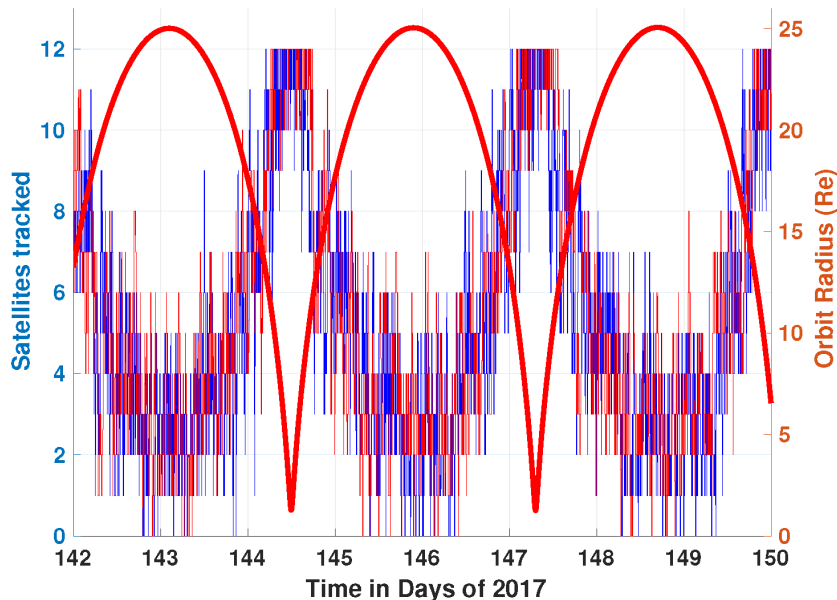


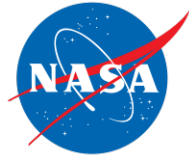


MMS2B calibration

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- Propagated initial state from flight data, same period as flight data plots
- Used GEONS-Datagen, with representative GPS Block IIR and IIRM 2D transmit antenna patterns obtained from www.gps.gov, to simulate signals (used IIRM for IIF also)
- Compared signals tracked and C/N_0 simulated vs. flight and adjusted receiver loss and GPS transmit power slightly per-block to line up
- Ran filter, looked at performance and compared to flight results (signals tracked, C/N_0 arcs, filter formal errors)
- Obtained a close *qualitative* match for all metrics
 - Did not model GPS transmitter yaw: sidelobe arcs don't match exactly
 - Randomness in acquisition model prevents exact match



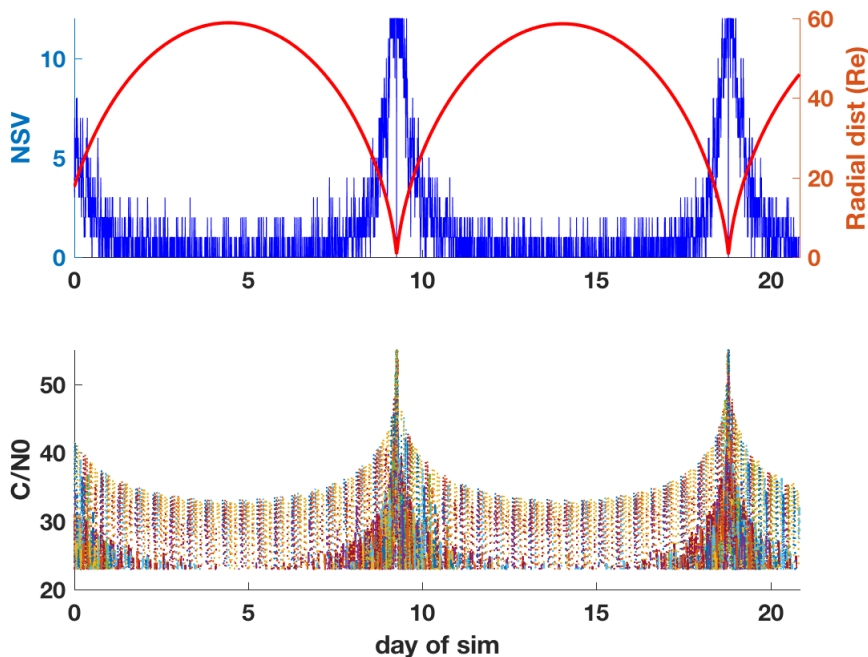


Concept MMS extended mission performance

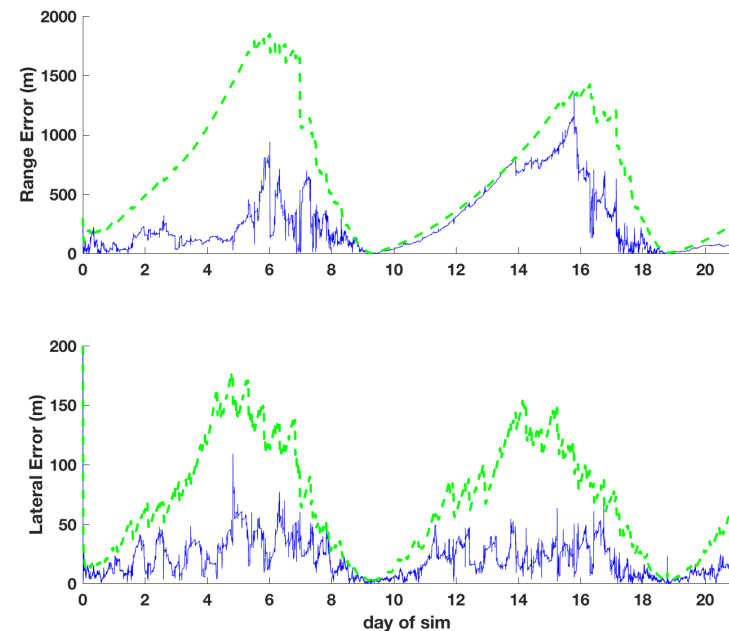
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- How will MMS-Nav perform if they raise apogee to 60 RE in extended mission?
- Propagated MMS4 initial state for 20+ days using “truth dynamics,” no maneuvers
- Use identical GEONS-Datagen configuration as in calibration, and similar filter config
 - plus some extra process noise near perigee
- Split errors in range/lateral direction
 - Range/clock errors become highly correlated and dominate total position error, performance limited by clock instability.

Signals tracked and radial dist (top); C/N_0 (bottom)



Filter position formal (3σ) and actual errors

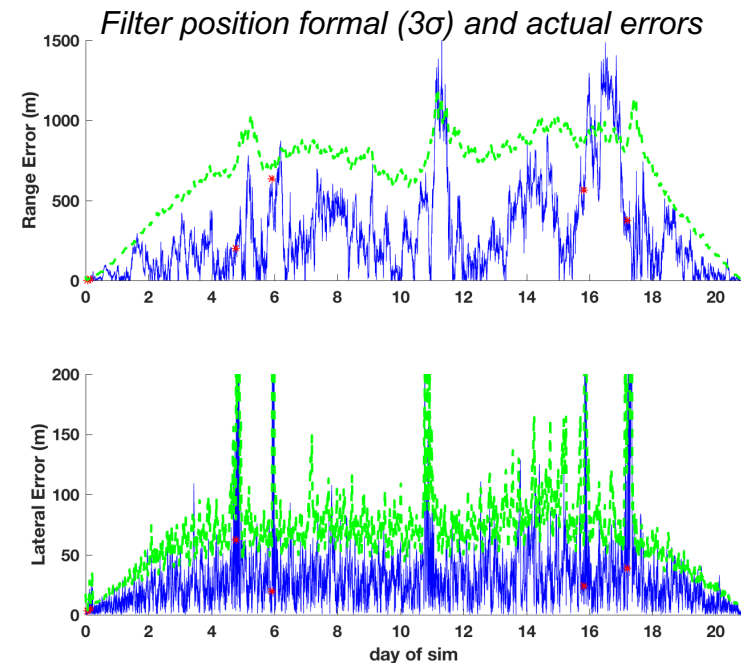
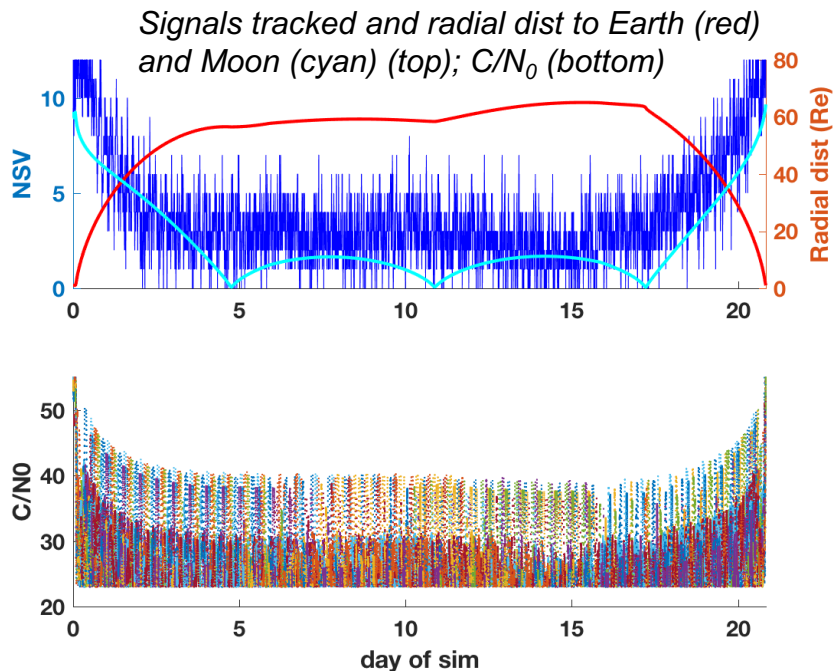


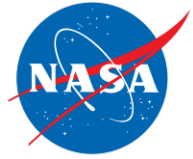


Concept Lunar mission

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- How will MMS-Nav perform if used on a conceptual Lunar mission with 14dBi high-gain?
 - GSFC internal research project aims to develop such an antenna
- Used concept Lunar trajectory:
 - LEO->translunar->Lunar (libration) orbit->return
- Use identical GEONS-Datagen configuration as in calibration, and similar filter config:
 - extra process noise near moon
 - high-gain switched on at 12RE
- Visibility similar to MMS2B, as high-gain makes up for additional path loss
- Again, range/clock-bias errors dominate
 - With atomic clock, or, e.g., periodic 2-way range/Doppler, could reduce range errors to meas. noise level





Conclusion

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- **High altitude GPS is now a proven technology that can reduce operations costs and even enable missions like MMS (and GOES-16 now)**
 - Applications and receiver availability expanding rapidly
- **MMS currently in Phase 2B orbit at 25Re (40% to moon) navigating onboard with GPS using GSFC-Navigator receiver + GEONS filter software**
 - *Highest (and fastest) operational use of GPS (already was case in Phase 1)*
 - Onboard navigation significantly out-performing requirements
 - Signal visibility throughout Phase 1 and even Phase 2B orbit is excellent
 - Sidelobe signals appear to be of “navigation quality”
- **Conducted simulations to predict MMS-nav system performance on two concept trajectories reaching Lunar distances**
 - Receiver should continue to perform very well for MMS extended mission
 - MMS-nav system with high-gain could offer strong onboard navigation performance for future Lunar exploration or habitation missions
- **High-altitude GPS navigation performance will only get better with new GNSS systems, signals, and receiver tech, but we believe useful onboard GPS navigation at Lunar distances is achievable *now* using *currently available signals* and *flight proven* receiver technology**